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SS2 Focusing Solenoid Quench Protection Study

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I. Introduction

Design of a focusing solenoid for the second superconducting section of the HINS linac (SS2) was described in [1].

Preliminary study of quench propagation and related protection issues for focusing solenoids in the superconducting sections of the HINS linac [2] has demonstrated that quench protection methods used for solenoids in the CH and SS1 section of the linac cannot be directly applied to the SS2 solenoids. With the "optimal" dump resistor, the maximum voltage to ground reaches 610 V, which exceeds the specified limit of 500 V. The main reason for this is that the stored energy in the solenoid is quite high. When a quench happens in one of the bucking coils, significant heating of the coil occurs with the corresponding rise of the coil resistance. This, in turn, results in a voltage drop across the quenching coil followed by the inductive voltage generated in the rest of the coils of the solenoid.

The analysis made in [2] used previously developed code [3] that did not take into account certain changes in the design of the SS2 solenoid made to simplify quench protection (e.g. the main coil was made consisting of two sections separated by a flange). Instead, to study quench propagation, an equivalent solenoid was used, which was similar to the SS1 or CH types. Difference between the two cases can be significant because the new design limits quench propagation to only one half of the main coil. So, the results obtained in [2] can only be used for a rough estimate of the quench propagation in the main coil (although this approach still should work fine if the quench develops in the bucking coil, which is the most vulnerable part of the solenoid). On the other hand, as was pointed out in [2], the self-inductance and mutual inductance calculation method used in the basic quench protection code [3] can result in some uncertainty. Ways to improve the code were also suggested.

This note describes improvements to the existing code to allow more rigorous analysis of quench propagation in the solenoid of the SS2 section and updates the quench propagation analysis of [2].

II. Mutual inductances in the SS2 focusing solenoid

To accurately calculate voltage drop in the coils of focusing solenoids, we need to find a way to calculate mutual inductances between layers in a single coil, between any coil and layers of another coil, and between any two of the solenoid coils. We start with mutual inductances between two circular turns and then develop expressions for mutual inductances for all the cases.

1. Turn-to-turn mutual inductance

By definition, mutual inductance between two turns (#1 and #2) is

$$M_{1,2} = \frac{\iint_{S2} (B \cdot n)\, dS}{I1} \qquad /1/$$

Here $I1$ is current in the turn #1, and the integral is taken on any surface that originates on the turn #2. Having in mind that $B = \nabla \times A$, we can re-write /1/ for the axially symmetric case as

$$M_{1,2} = \frac{\iint_{S2} ((\nabla \times A) \cdot n) dS}{I1} = \frac{\oint_{\Gamma_S} (A \cdot t) dl}{I1} = \frac{2 \cdot \pi \cdot R \cdot A_{Phi}}{I1} \qquad /2/$$

2. Layer-to-layer mutual inductance

Mutual inductance between two layers in one coil (M_L1L2) can be found using /1/. By definition, we can write down:

$$M\_L1L2 = (\sum \Psi 2_i)/I1 \qquad /3/$$

where $\sum \Psi 2_i$ is a sum of magnetic fluxes through all the turns in the layer #2 due to the magnetic field generated by the layer #1. Having in mind that $\Psi 2_i = 2 \cdot \pi \cdot R2 \cdot A2_i$, and the length associated with one turn in the coil #2 is $dl = l2/w2$ ($l2$ is the length of the layer #2 and $w2$ is the number of turns in the layer), we can write down taking into account /2/:

$$M\_L1L2 = 2\pi / J1 \cdot (w1 \cdot w2) / (l1 \cdot l2) \cdot \int (A2_i \cdot R2) dl, \qquad /4/$$

where ***J1*** is a linear current density in the source layer.

If the coil consists of N layers, the mutual inductance between its layers can be represented as a rectangular array $\boldsymbol{M_{i,j}}$ of size (N x N). In this array, the diagonal elements $\boldsymbol{M_{i,i}}$ are inductances of the layers. A vector **sum($\boldsymbol{M_{i,j}}$)** is a "reactance" vector, which defines what voltage will be generated across the layer "***i***" if the current in the coil changes. The inductance of the coil by taking a sume of all the elemnts in the matrix:

$$L = \text{sum}(\text{sum}(M_{i,j})) \text{ or } L = \sum_i \sum_j M_{i,j} .$$

To check this approach, inductances of several sample coils calculated using this method were compared with evaluation provided by different handbooks. The agreement between the two approaches was quite satisfactory.

3. Coil-to-layer mutual inductance

When we need to find mutual inductance between one of the coils in the solenoid and a layer in another coil, a procedure similar to that for the layer-to-layer inductance can be applied. The only difference is that now it is more convenient to use an area current density in the source coil. Corresponding expression is provided below:

$$M\_C1L2_i = 2\pi / J1 \cdot (N1 \cdot w2) / (S1 \cdot l2) \cdot \int (A2_i \cdot R2_i) dl \qquad /5/$$

Here ***N1*** is the number of turns and ***S1*** is the cross-section of the source coil (#1), ***w2*** is the number of turns and ***l2*** is the length of a layer in the coil #2. This inductance must be found for layers of each coil with respect to any other coil. If the solenoid consists of four coils (as it is for the SS2 solenoid) we need to find twelve vectors of the coil-to-layer mutual inductances. In our case, the system symmetry helps to reduce this number to six. The sum of elements in each vector gives corresponding coil-to-coil mutual inductance.

4. Coil-to-coil mutual inductance

Coil-to-coil mutual inductance can be found in a way similar to how it was made before:

$$M\_C1C2 = 2\cdot\pi\cdot(N1\cdot N2)/(S1\cdot S2)\cdot 1/J1 \cdot\int(R2\cdot A2_i)\cdot dS \qquad /6/$$

In the case of the SS2 solenoid, which contains four coils, the full set of the coil-to-coil mutual inductances forms a 4x4 array with diagonal symmetry (because $M\_C1C2 = M\_C2C1$). Diagonal elements of the array are inductances of the individual coils. The sign of an induction coefficient for two coils in the inductance matrix is positive if the two coils have unidirectional magnetic fields. If the directions of the field is opposite for the two coils, the sign of the corresponding induction coefficient is negative.

To get needed information about mutual inductances in the focusing solenoid coil system, we need to find vector potential ***A*** on the surfaces (or in the volume) of the non-source coil (or a layer of a coil). Because there are many layers in each coil, the amount of the needed information becomes quite big, which can result in significant time spent in collecting this information. The situation can be relaxed by obtaining the needed data only at several layers within the coil and then using interpolation to expand the data to all the layers of the coil of interest. This interpolation can be conveniently made using MATLAB interpolation functions: INTERP1(X,Y,Z,XI,YI) for vectors and INTERP2(X,Y,Z,XI,YI) for two-dimensional arrays. The data preparation process consists of the following steps:

- Use COMSOL (or other magnetic modeling program) to find values of the vector potential in the system.
- Within the non-source coil geometry, place several layers to generate a reduced (sample) matrix of layer's mutual inductances.
- Using expressions /4/, /5/, or /6/, find a matrix of mutual inductances for the chosen system of the sample layers (or coils). Because these matrices are symmetrical, the order of the indices is not important.
- The resultant "sample" matrices of mutual inductances are embedded into the input file of the quench protection code.
- Using the matrix interpolation functions, the obtained matrices are expanded to correspond to the number of layers in the coils (inside the input file of the quench protection code).

III. <u>Voltage in focusing solenoid coils</u>

The voltage distribution in a quenching coil is defined by the voltage drop across the resistive section in the coil and by the inductive component. The inductive component of the voltage for each layer is defined by the layer inductance, mutual inductances between all other layers of the same coil and this particular layer, and between the rest of the coils in the solenoid and the layer of interest. So, the voltage distribution inside the quenching coil depends on the quench start location and on the rate of the quench propagation through the coil, which defines the coil resistance change and the circuit current decay rate. Voltage to ground is also defined by the location of the ground point within the solenoid discharge circuit.

The layer-to-layer mutual inductances are calculated as shown in the section II-2 of this note. To find the voltage in the layer, we will use the so-called "reactance" of the layer, which is a sum of layer-to-layer mutual inductances for the particular layer, including the mutual inductance with the same layer (which is the self-inductance of the layer). Technically this means taking a sum of elements in a row (or column) of the mutual inductance matrix M_LiLj that contains the layer of interest.

The coil-to-layer mutual inductances are introduced in the section II-3. Sign rule from the section II-4 must be also followed here.

As an example, calculation of the voltage gain in each layer of the quenching BC1 coil in the SS-2 solenoid is made using the next expression:

$dU\_layer_i = It*Rlayer_i + dIdt*\{React\_Layer(BC1\_Li) + BC2\_BC1Li - MC1\_BC1Li - MC2\_BC1Li\}$ /7/

The total voltage drop in the quenching coil is found by summing voltages across all the layers in the coil.

For the coils that do not experience quench, the voltage drop is pure inductive and is defined by the “reactance” of the coil, which is a sum of the coil inductance and the mutual inductances between the rest of the coils and the coil of interest. Technically this is made by summing all elements in a row or a column of the coil-to-coil mutual inductance matrix (see section II-4), which contains the coil of interest. The mutual inductance sign rule must be followed here, so some elements in the matrix have the negative sign.

Because the inductive part of the voltage is proportional to the circuit current decay rate, it is important to properly calculate the circuit inductance. Having the coil-to-coil mutual inductance matrix defined, the total inductance can be calculated by summing all elements in the matrix.

The voltage to ground depends on the solenoid discharge circuit configuration. The SS-2 solenoid design was made in a way to allow grounding the central turn in the inner layer of the main coil to reduce the voltage to ground (see Fig. 1). Study of this case is the subject of this note.

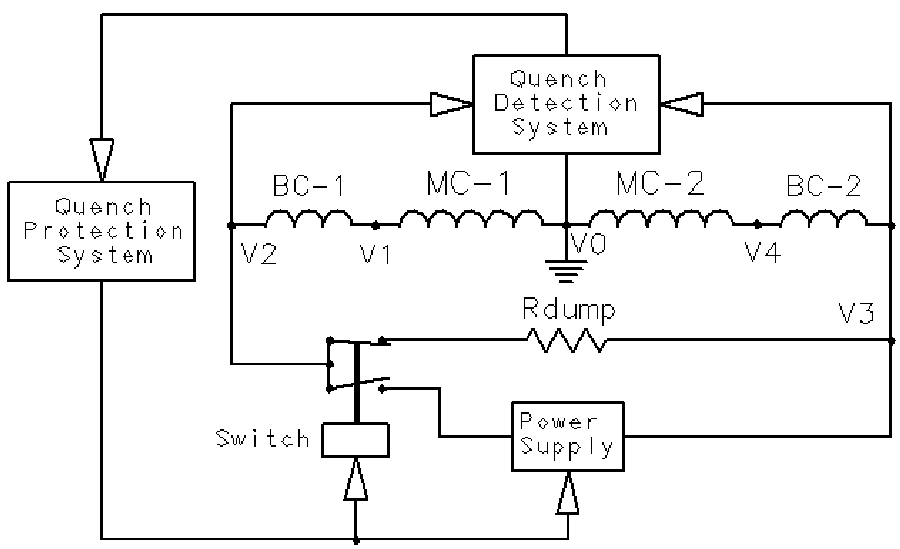


Fig. 1: Simplified focusing solenoid quench protection circuit diagram

Initially the solenoid, consisting of the coils BC1, MC1, MC2, and BC2 is powered by a power supply. After quench is detected in one of the coils, the power supply is disconnected, and a dump resistor is introduced in the discharge circuit. This moment defines the start of the modeling. The value of the dump resistor defines the initial current decay rate and, in the end, the amount of the energy removed from the solenoid.

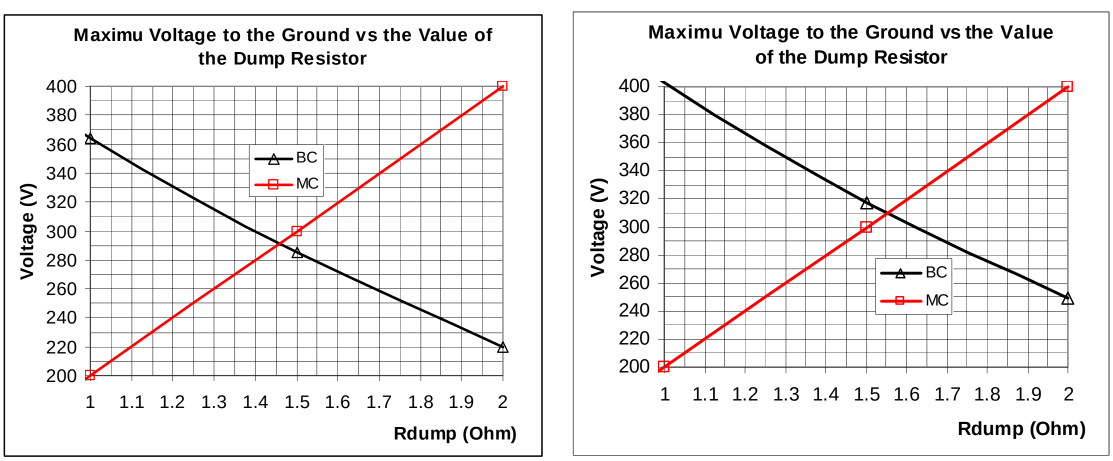
IV. Code verification

Before proceeding with a study of the SS2 solenoid protection, the updated code was verified by recalculating quench propagation in the SS1_PP solenoid, that was earlier reported in [2]. A comparison of the two approaches was made for the case when quench starts in one of the bucking coils. Table 1 below compares inductances of the main and the bucking coils obtained using the two techniques:

Table 1: Comparison of the inductances used in [2] and obtained by the new approach

	Old Method	New Method
MC Inductance (H)	0.28	0.305
BC Inductance (H)	0.015	0.022
Mutual inductance MC-BC (H)	neglected	-0.017
Mutual Inductance BC-BC (H)	neglected	2.4e-5
Solenoid inductance (H)	0.31	0.32

The difference in the inductances of the bucking coils is explained by different inner radius of the bucking coils used for these two cases. In spite of some differences in the inductances of particular coils, the total solenoid inductance is about the same for the two approaches (this result is quite accidental: this happened because in the "old" case the mutual inductances between the coils were neglected). Nevertheless, we can expect some variations in the voltage distribution in the quenching coil. Fig. 2 compares the voltage-to-ground diagrams for the two approaches that show expected voltages in the discharge circuits for different dump resistances.



a) b)

Fig. 2: Voltage-to-ground diagram for the case of the quenching bucking coil:
a) using the "old" approach; b) using the "new" approach

The 'new' approach shows higher voltage generated in the quenching bucking coil. As a result, the optimal resistance becomes a bit higher than what is currently used is the solenoid test setup. Nevertheless, the new results are quite comparable with the old findings, and no corrections are needed for the chosen protection scheme.

V. <u>SS2 focusing solenoid quench protection study</u>

At this stage, we will consider only quenches in one half of the main coil or in one bucking coil. Because a quench in the bucking coil is potentially the most dangerous situation, it is natural to start with this case. Nevertheless, as only one half of the main coil quenches, we need to verify that the quenching half does not overheat and that the voltage generated during quench is sufficiently low. The current discharge scheme in Fig. 1 will be used for voltage calculation.

1. Quench in one of the bucking coils; Rdump = 0

First, the case with no dump resistor in the circuit will be analyzed and results will be compared with what was obtained in [2] at I0 = 250 A. The location of the initial quench point is at the position of the minimum magnetic field in one of the bucking coils, which is Nt = 10 and Nl = 18 (the location Nt = 1 is the closest to the main coil). Figures 3 to 5 show the circuit current, maximum temperature in the coil, the quenching coil resistance, and the voltage across the quenching coil.

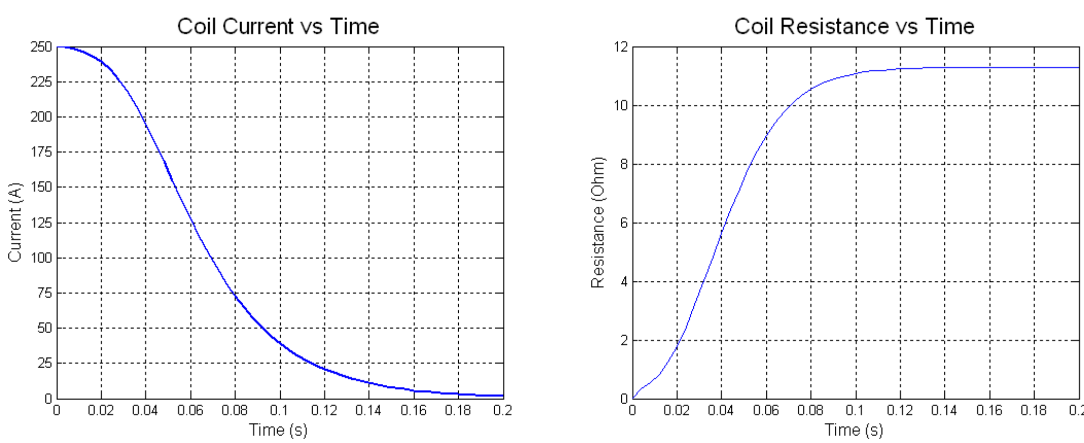


Fig. 3. Current in the discharge circuit and bucking coil resistance; Rdump = 0

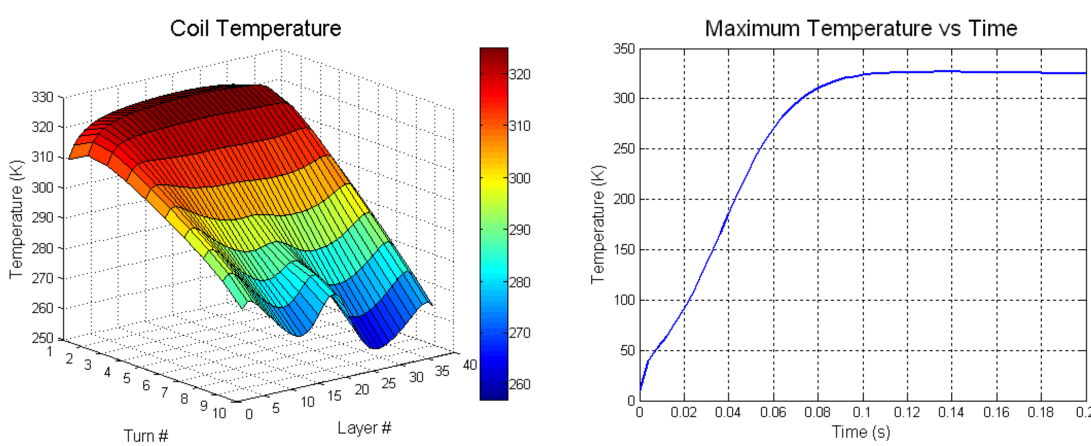


Fig. 4. Quenching bucking coil tetmperature; Rdump = 0

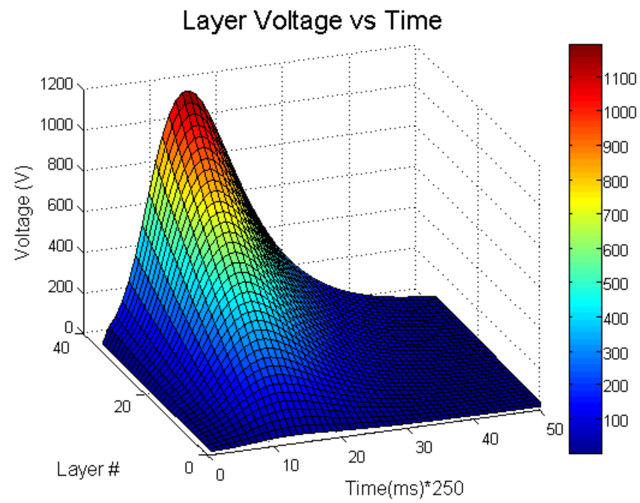
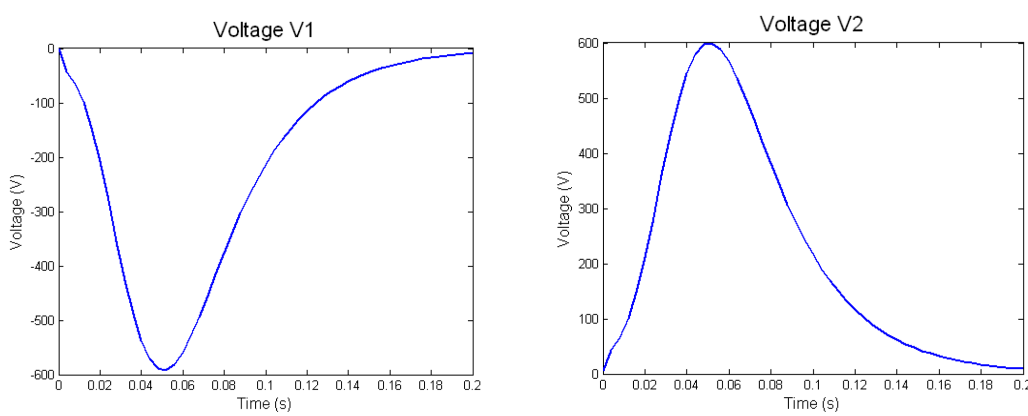


Fig. 5. Relative layer voltage in the quenching bucking coil; Rdump = 0.

The maximum temperature in the coil reaches ~330 K, which is unacceptable. The voltage across the quenching coil is also high; voltage to ground on both sides of this coil is ~600 V as we can see from the plots in Fig. 6. The difference between the data set in Fig. 6 gives the relative voltage of the last (36-th) layer in the coil in Fig. 5.



a) b)

Fig. 6. Voltage to ground: a) between the quenching bucking coil BC1 and the main coil (V1); b) between the two bucking coil (V2); Rdump = 0

2. Quench in one of the bucking coils; Rdump > 0

To reduce voltage to ground and temperature in the coil, we will first employ a dump resistor. A diagram in Fig. 7 below shows how the coil temperature and voltages along the circuit depend on value of the dump resistor. As earlier, Fig. 1 specifies the location of points in the circuit where the voltages V0, V1, V2, V3, and V4 are measured. The diagram shows a shallow minimum of the maximum voltage at Rdump ≈ 2.9 Ohm. The maximum temperature is below 300 K at Rdump > 1 Ohm.

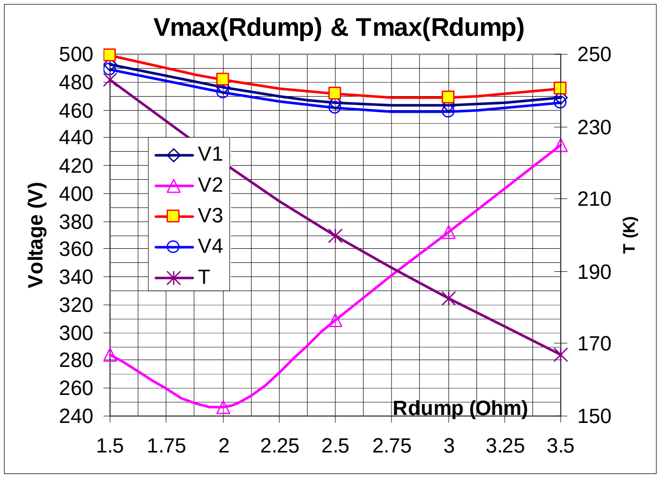
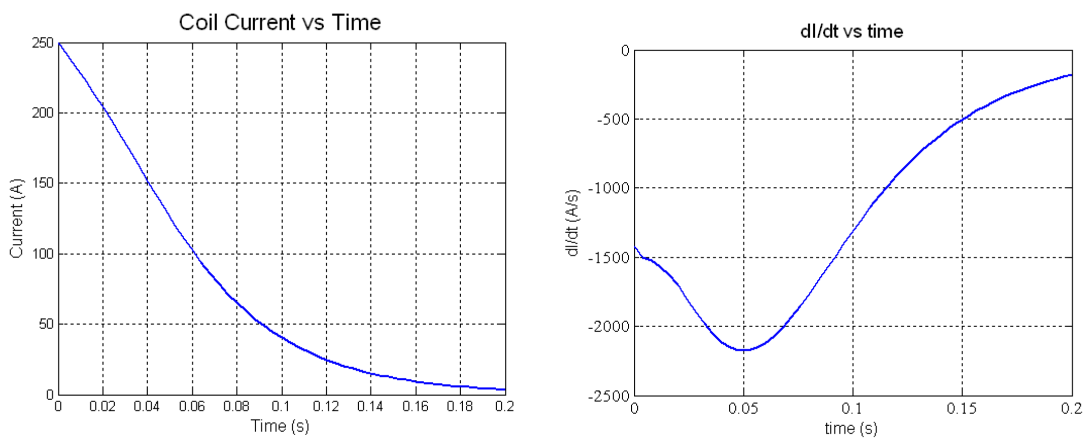


Fig. 7. Diagram of the maximum voltage in the circuit and temperature in bucking coil.

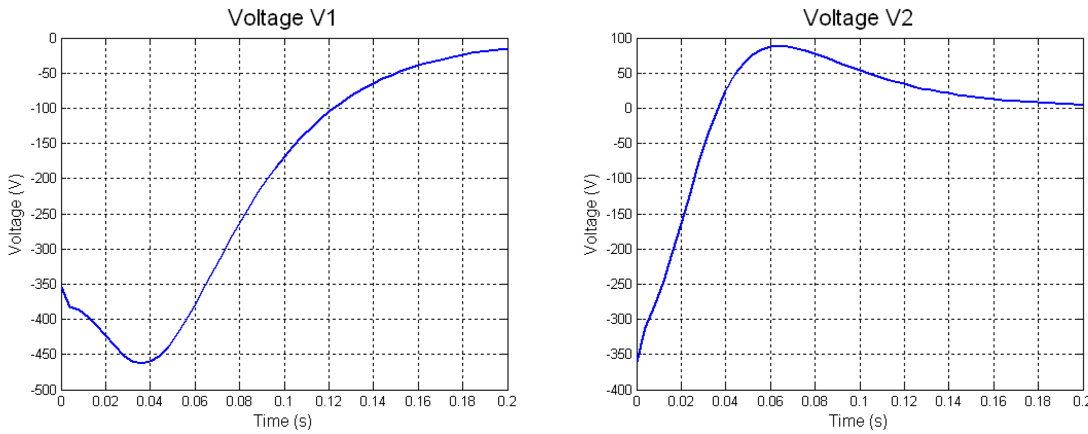
With the dump resistance of 2.9 Ohm, dissipated in this resistor energy is 6.48 kJ (I0 = 250 A) or 59% of the total energy stored in the magnetic field of the device. The maximum temperature in the coil is 186 K. The maximum voltage across the quenching coil reaches ~380 V at the moment t = 0.06 sec after the quench. Graphs in Fig. 8 show the circuit current and its time derivative for this case.



a) b)

Fig. 8. Current in the discharge circuit (a) and its time derivative (b); Rdump = 2.9 Ohm

Fig. 9 shows voltage to ground at the points around the quenching bucking coil. The difference between the voltages V1 and V2 gives the voltage across the quenching coil, which is shown in Fig. 10.



a) b)

Fig. 9. Voltage to ground: a) between the quenching bucking coil BC1 and the main coil MC1; b) between the quenching BC1 and the dump resistor; Rdump = 2.9 Ohm

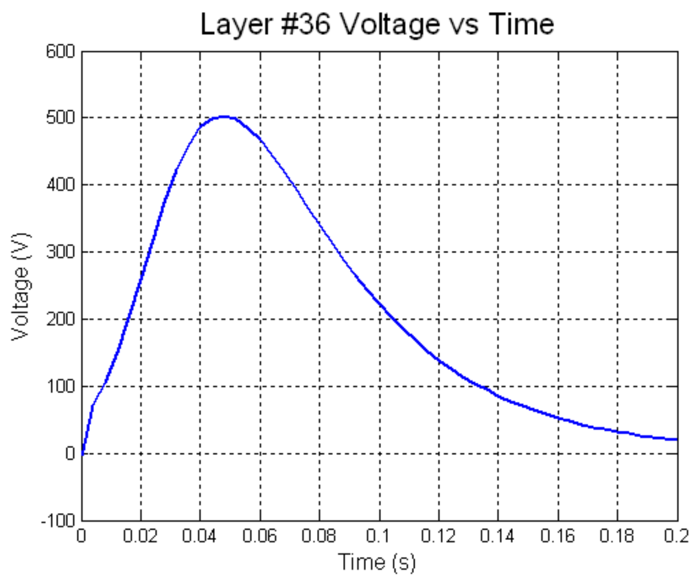


Fig. 10. Voltage across the quenching bucking coil; Rdump = 2.9 Ohm.

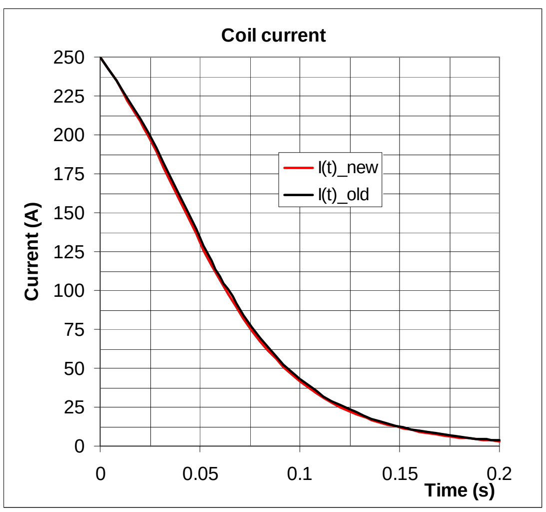
As mentioned earlier, if inductances of the coils and mutual inductances between circuit elements in the discharge circuit are estimated correctly, one should not expect any significant difference in results obtained in this study and that in [2] because the main coil participates in the quenching process not actively, but only through its inductive connections. Having this in mind, a comparison with the previously obtained results was made to understand how far apart the two cases are, which can indicate hidden traps in the calculation algorithm. Table 2 below compares main results obtained by using the two approaches to calculate quench propagation in one of the bucking coils for corresponding optimal dump resistor values: Rdump = 2.45 Ohm for the “old” case [2] and Rdump = 2.9 Ohm for the “new” case.

Table 2: Comparison of results obtained in [2] and using the new approach

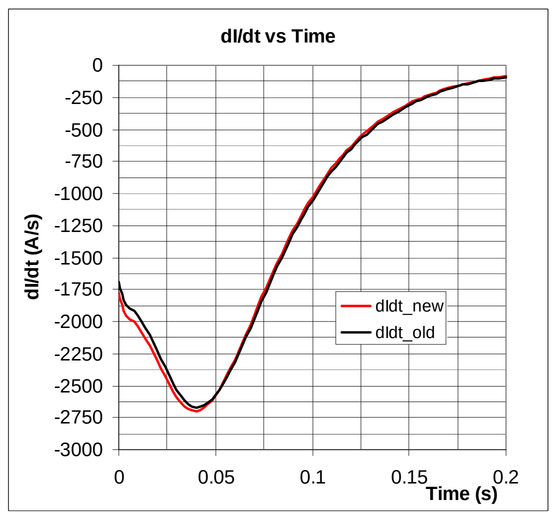
	Result obtained in [2]	"New" results
Optimal Rdump (Ohm)	2.45	2.9
Maximum temperature (K)	240	186
Maximum coil resistance (Ohm)	7	5.8
Voltage across the quenching coil (V)	600	500

The new approach shows lower coil temperature (because of higher value of the optimal dump resistor) and lower voltage across the quenching coil.

It is also interesting to compare the two cases with the same dump resistance. Figures 11 to 13 below compare coil current, its time derivative, coil resistance, voltage across the quenching coil, and the coil maximum temperature for the "old" and "new" cases for Rdump = 2.5 Ohm. As one should expect, the results are quite close.

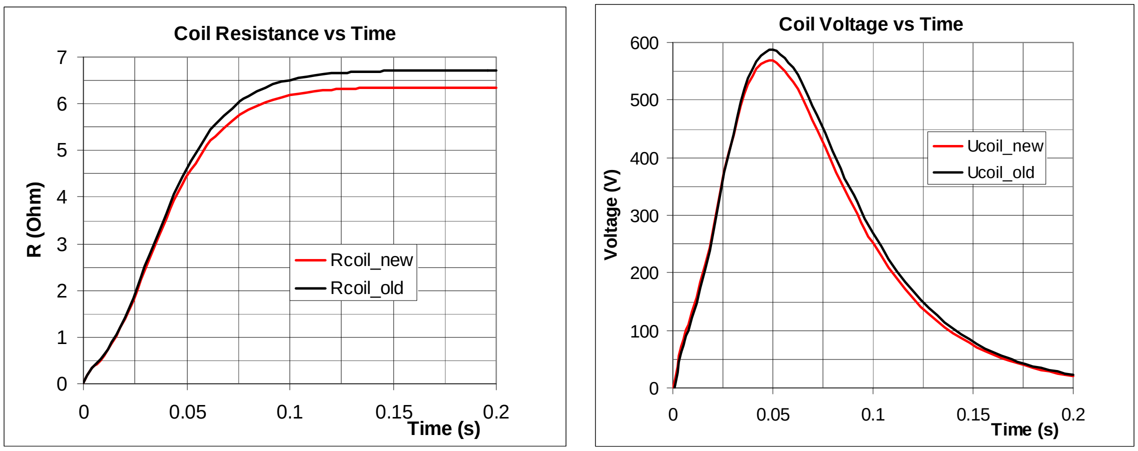


a)



b)

Fig. 11. Current (a) and its time derivative (b) in the discharge circuit



a) b)

Fig. 12. Quenching coil resistance (a) and voltage across the quenching coil (b)

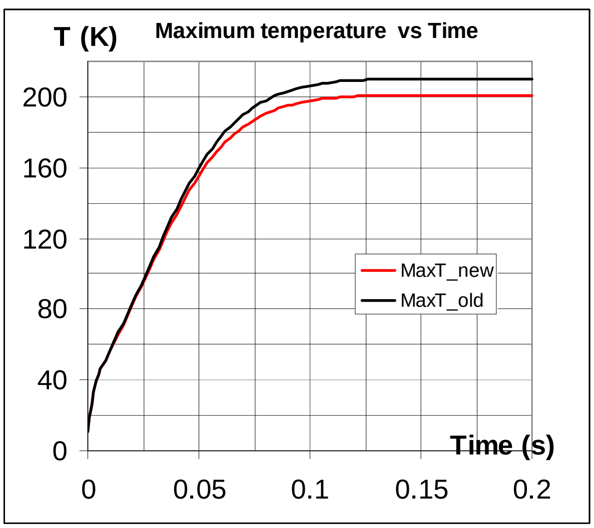


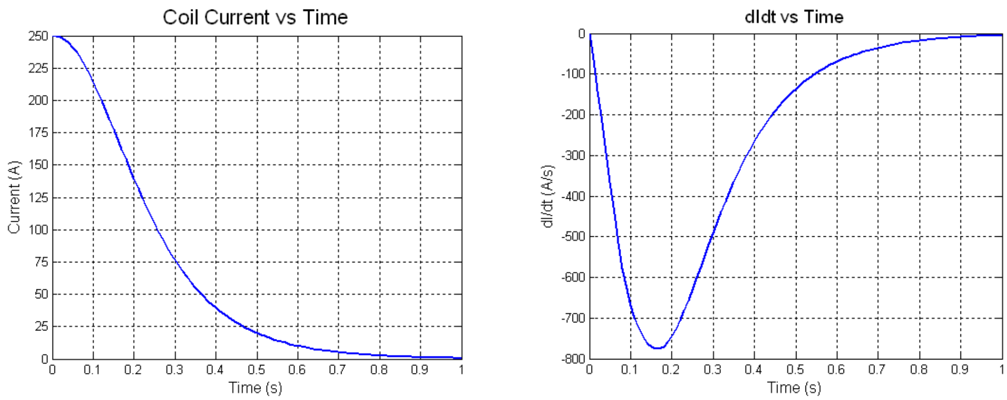
Fig. 13. Maximum temperature in the coil

Analysis of the results shows that the updated program works well, providing trustable data about quench propagation in quenching coil of a focusing solenoid.

It has been shown that, if the quench happens in the bucking coil, we can use the protection technique previously employed for the SS1 solenoid quench protection with the value of the dump resistor close to the optimal value of ~2.9 Ohm. The question remains whether this value of a dump resistance is safe in the case when the quench happens in the main coil.

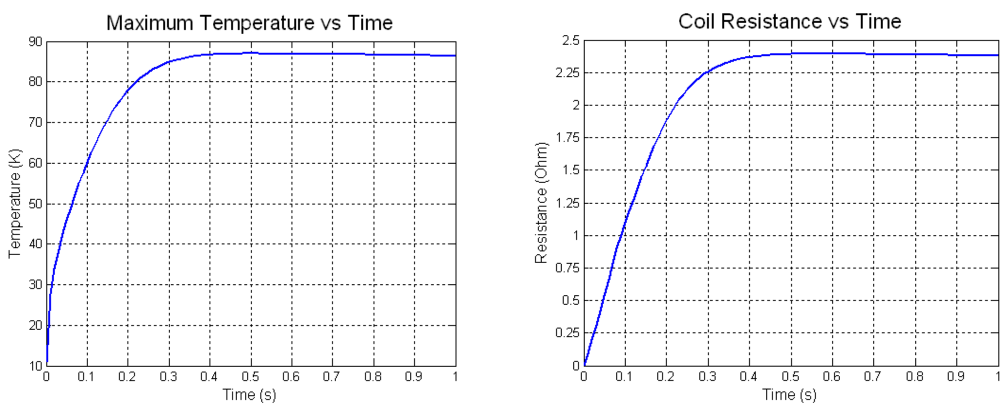
3. Quench in one half of the main coil; Rdump = 0

We will start with the case of no dump resistor in the discharge circuit. The current in the circuit before the quench is 250 A, and quench initiation point is located in the inner layer of one half of the main coil in the area of the maximum magnetic field. Figures 14 to 16 show the circuit current and its derivative, maximum temperature in the coil, the quenching coil resistance, and the voltage to ground in the quenching coil.



a) b)

Fig. 14. Solenoid current (a) and its derivative (b) after quench in MC1; Rdump = 0.



a) b)

Fig. 15. Maximum temperature in the quenching MC-1 coil (a) and the coil resistance (b): Rdump = 0.

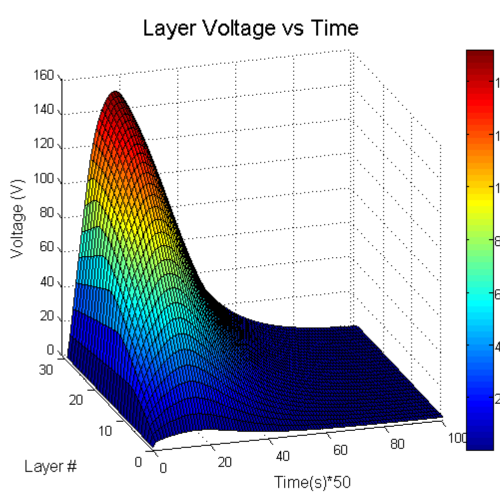


Fig. 16. Quenching main coil layer-to-ground voltage; Rdump = 0

For the rest of the solenoid's coils, the voltage to ground is less than that for the quenching half of the main coil. So, there is no danger for the quenching main coil even without a dump resistor in the discharge circuit. Nevertheless, a dump resistor must be added to protect a quenching bucking coil, and we need to investigate possible impact of this resistance on the voltage to ground distribution in the case of a quenching main coil.

4. Quench in one half of the main coil; Rdump > 0

Adding a dump resistor increases voltage to ground in the circuit. Fig. 17 shows the absolute value of voltage to ground along the discharge circuit of Fig. 1. Even with Rdump = 3.5 Ohm, the highest voltage is still below 500 V.

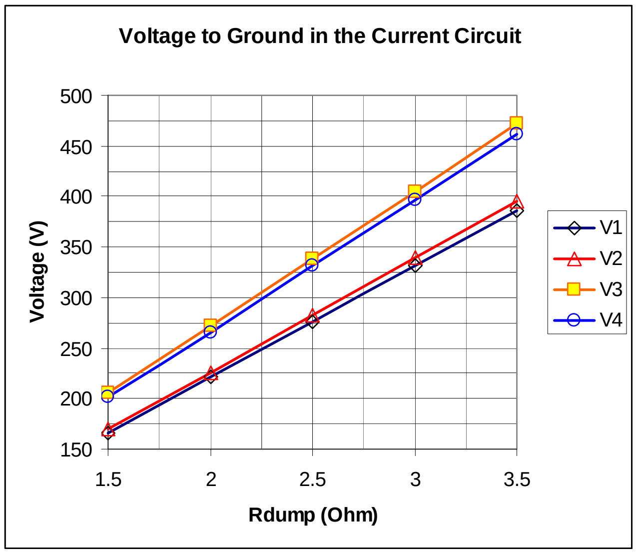


Fig. 17. Voltage to ground in the discharge circuit as a function of the dump resistance with the quench in the main coil.

VI. Conclusion

This quench protection study can be summarized as follows:

1. The new code allows analysis of complex combination of inductively connected coils, like in the focusing solenoids, providing accurate evaluation of the inductances.

2. The updated quench protection code works as expected. The results obtained using this code are well comparable with those obtained using the old code [2, 3].

3. The analysis made using the "new" code with new discharge circuit configuration proves that the SS2 solenoid can be protected by employing a dump resistor, similar to what was done earlier for the SS1 solenoid protection. The optimal value of the dump resistor is ~2.9 Ohm.

With this conclusion, further improvements can be made to the code. Additional quench protection techniques, like using a parallel, distributed protection schemes and cold diodes, can be investigated to choose the most reliable for implementation in the quench protection system of HINS linac. Simultaneous quenching in more than one coil can be introduced in the code to allow studying more sophisticated, and potentially advantageous, protection schemes.

References:

1. G. Davis, et al, "HINS Linac SS2 Section Prototype Focusing Lens Design, TD-09-003, FNAL, March 2009.
2. I. Terechkine, "Quench Protection Study for the Solenoids of Superconducting Sections of HINS Linac", TD-09-002, FNAL, February 2009.
3. I. Terechkine, V. Veretennikov, "Normal Zone Propagation in Superconducting Focusing Solenoids and Related Quench Protection Issues", IEEE Transaction on Applied Superconductivity, v. 18, No. 2, pp. 1325 – 1328, June 2008.

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